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Simulation of the effect of insulation surface condition on electrical characteristics in HVDC cables

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Abstract. During the manufacturing process of HVDC cables, the insulation layer's surface often exhibits micro-sized defects. These defects can affect the electrical properties of the power cable, thereby influencing the aging process, insulation breakdown, and reliability of the HVDC cable in high-voltage direct current transmission systems. To investigate the influence of different surface conditions on the electrical characteristics of HVDC cables, this paper conducts 2D simulations on XLPE insulation material samples of a mini HVDC cable. The simulations incorporate various surface conditions of the insulation layer, including an ideal smooth surface, independent defects, and clustered defects, to examine the variations in internal electrical characteristics such as space charge distribution and electric field distribution inside the insulation layer. The simulation results indicate that the presence of non-ideal surface conditions significantly affects the electrical properties of the insulation layer, as well as adversely impacts the reliability of the HVDC cable in power transmission systems. The differing degrees of influence from various surface conditions and their causes are also discussed in this paper.

Keywords: HVDC cable, XLPE insulation, surface defects, space charge, electric field distribution.

1 Introduction

Currently, the high-voltage power transmission system using High Voltage Direct Current (HVDC), are increasingly being used, particularly in connecting transmission grids from distributed power sources such as offshore wind farms, long-distance power transmission, or submarine power transmission lines [1]. This is achieved with the assistance of HVDC power cables, AC/DC converter stations and DC/AC inverter stations. For HVDC cables, insulation is commonly used in the form of synthetic organic materials (polymer) and oil insulation, in which oil insulation is gradually being replaced by polymer insulation [2] due to cost disadvantages and environmental concerns. One of the main problems for polymer-insulated cables is preventing the accumulation of space charge inside the insulation, as it is a factor that causes premature aging, reduces insulation capability, and shortens the cable lifespan [3-5]. During the operation of power transmission cables, under the influence of applied voltage and external factors, space

charges are generated, move, and change the electric field distribution inside the cable insulation. These space charges tend to be generated more and exhibit more flexibility when the cable is subjected to high thermal-electric stress. One of the factors influencing the electric field and space charge distributions inside the cable insulation is the condition of the cable insulation surface, including its contact with the conductive part and cover parts of the cable. Surface defects on the insulation can change the insulation layer thickness, leading to change the electric field value when the applied voltage to the HVDC cable remains unchanged.

Surface defects on the insulation appear during the manufacturing process and have sizes ranging from a few nanometers to a few micrometers, occurring regularly [6]. Studies on the influence of surface defects on the electric field variation and space charge distribution have been conducted through simulations, mainly on flat and thin insulation film samples [6-9]. The results have shown that surface defects alter the rate and intensity of the electric charge injection process into the insulation material, leading to increased electric field reactions. Some research groups have also conducted studies on power cables with bigger defects inside the insulation [10], demonstrating a significant impact of defects on the electric field and insulation strength of the cable. Such significant defects can form during cable incidents, such as partial discharges, or less commonly, during the manufacturing and installation processes.

In this study, we focus on examining the influence of surface defects on the electrical characteristics of HVDC cables. These types of defects frequently occur in practice but have not been extensively studied domestically. The approach of modeling the solid insulation material of the power cables has been utilized by some research groups in the world. It allows simulating the electrical responses of the dielectric, mainly assuming a smooth and ideal contact surface with the electrode [11,12]. A 2D space charge transport model [8] of the cross-linked polyethylene (XLPE) material, developed from a 1D model [11], will be used by the research team to simulate the electrical characteristics in the insulation layer. This numerical model is developed based on the finite element method using Comsol Multiphysics® software, enabling the integration of various physical processes occurring inside the polymer dielectric to describe its electrical characteristics. The shape of the polymer insulation, as well as the shape and position of defects, will also be modeled with different options. This model will help the research team investigate the influence of different surface conditions on the electrical characteristics of the polymer insulation in HVDC power cables.

2 Modeling the Insulation Layer of HVDC Cable

2.1 HVDC Cable Insulation Sample

The insulation layer is one of the most important components of a power cable, along with the conductor core. Typically, a polymer insulation layer is placed between two thin semiconductor (SC) layers, surrounding the conductor core as shown in Figure 1.

In this study, a cable used as a reference is a 320kV-1000MW high-voltage direct current (HVDC) submarine cable with a 20mm thick XLPE insulation layer.

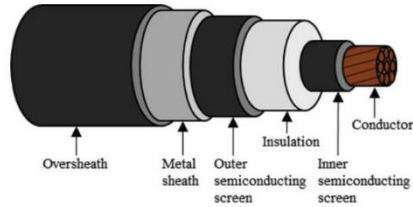


Fig. 1. Structure of an HVDC cable [13]

The surface condition of the insulation layer of the cable is considered to be ideally smooth or may contain micro-sized defects. These small-sized defects have a minimal impact on the space charge distribution inside the cable insulation, occupying a small area that does not affect the entire thickness of the cable. Therefore, to save computational time in simulations, we use a scaled-down material sample (a mini cable). Specifically, the simulation will be carried out on a mini cable with a diameter equal to 1/100 of the actual cable, and the insulation layer in the simulation will have a thickness of 0.2mm. The corresponding DC voltage applied to the cable will be 3.2kV to maintain the electric field value applied to the cable. The insulation sample is extracted from the mini cable and takes the form of a circular rim with a 5° opening angle, as shown in Figure 2. The positive pole of the voltage source is placed on the inner part of the insulation layer close to the cable core, while the negative pole ($V=0$) is placed on the outer part of the insulation layer towards the cable sheath.

Simulations use the assumption of equi-potential in the semiconductor layer between the cable core and the insulation layer, during the conduction process. Therefore, the applied voltage on the insulation sample in the study is 3.2 kV, corresponding to an electric field of 16 kV/mm.

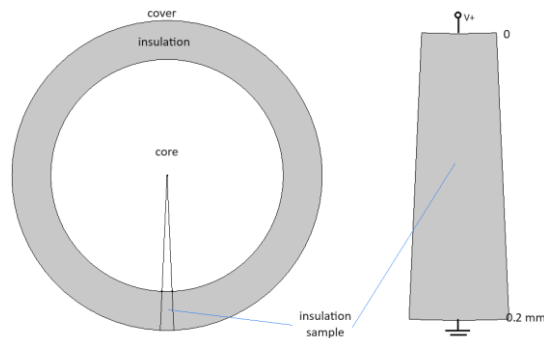


Fig. 2. Cable insulation sample – a $5/360^\circ$ circular rim

2.2 Charge Transport Model in XLPE Insulation Layer

The simulations in this study are based on a two-dimensional (2D) charge transport model, which has been previously developed [8, 11]. This model integrates physical hypotheses related to the microstructure of the polymer insulation material. Inside the material, there are two main types of charged particles: negative charge carriers (electrons) and positive charge carriers (holes). Each type can exist in two states: free and trapped (in potential wells). The charges within the dielectric are injected by the Schottky mechanism [14] from the electrodes and depend on the external electric field and temperature. The charges can move within the dielectric through a hopping mechanism (trap-to-trap) from one trap to another. This charge transport mechanism is characterized by a constant mobility coefficient for each type of charge. During trapping, the charges are assumed to be trapped at a single energy level and are characterized by a trapping coefficient. The charges are released by thermal excitation. The recombination of opposite charges into neutral atoms is also considered in the model with constant parameters. The physical assumptions of the 2D charge transport model are described by mathematical equations, which can be found in previous publications [11].

To obtain the electrical characteristics of the cable under thermal-electric stress, including the space charge density, electric field distribution as a function of the thickness and width of the insulation sample, and the external current density, a set of equations (Poisson, transport, and continuity equations) are solved using the finite element method (FEM) with the Comsol Multiphysics® simulation software.

Poisson equation:

$$\frac{\partial E(r,t)}{\partial r} = \frac{\rho(r,t)}{\varepsilon_0 \varepsilon_r} \quad (1)$$

Transport equation:

$$j_a(r,t) = \mu_a n_a(r,t) E(r,t) \quad (2)$$

Continuity equation:

$$\frac{q \partial n_a(r,t)}{\partial t} + \frac{\partial j_a(r,t)}{\partial r} = s_a(r,t) \quad (3)$$

where E is the electric field intensity, q and ρ represent the charge value and charge density in the dielectric; ε_0 and ε_r are the absolute and relative permittivity constants, r is the radius coordinate, a represents the electron (e) and hole (h), j_a is the current density, n_a is the charge density, and μ_a is the mobility coefficient of the considered particles, s_a represents the source term, describing the occurrence and disappearance of charges unrelated to the transport process, including trapping, release, and recombination.

To simulate the electrical characteristics of XLPE insulation samples, this study uses previously determined microstructural parameters from semi-experimental studies on low-density polyethylene (LDPE) [11] and XLPE [15] materials, as shown in Table 1.

Table 1. Insulation sample parameters

Symbol	value	units
Trapping coefficients		

B_e electrons	$1 \cdot 10^{-1}$	s^{-1}
B_h holes	$2 \cdot 10^{-1}$	s^{-1}
Mobility for x and z axis		
μ_e for electrons	$1 \cdot 10^{-14}$	$m^2 \cdot V^{-1} \cdot s^{-1}$
μ_h for holes	$2 \cdot 10^{-13}$	$m^2 \cdot V^{-1} \cdot s^{-1}$
Hopping barrier		
w_e for electrons	0.3	eV
w_h for holes	0.3	eV
Trap densities		
N_{oet} for electrons	$6.25 \cdot 10^{20}$	m^{-3}
N_{oht} for holes	$6.25 \cdot 10^{20}$	m^{-3}
Injection barrier heights		
w_{ei} for electrons	1.24	eV
w_{hi} for holes	1.16	eV
Relative permittivity		
	2.3	
Detrapping barrier heights		
w_{tre} for electrons	0.96	eV
w_{trh} for holes	0.99	eV

3 Influence of the Surface Condition of the Insulation Layer on the Electrical Characteristics of HVDC Cables

This study focuses on the influence of the surface condition on the electrical characteristics of the cable, which are the space charge distribution and electric field distribution within the dielectric. Two surface conditions are considered: an ideal smooth surface and a surface containing defects in the form of concave hemispheres with a radius of $1 \mu m$. In the latter case, the positions and quantities of the defects are also varied in the simulations. In all simulations performed, a DC field of $16 kV/mm$ is applied to the insulation sample for a duration of one hour to observe the variations of electrical characteristics as a function of the time.

3.1 Influence of the Surface Condition of the Insulation Layer on the Space Charge Distribution

Ideal smooth surface of the XLPE insulation layer:

The space charge distribution within the XLPE insulation layer with an ideal smooth surface when a $16 kV/mm$ DC field is applied to the HVDC cable is illustrated in Figure 3. Once the voltage is applied to the cable, space charges are injected into the insulation layer, from two electrodes, with positive charges injected from the anode and negative charges injected from the cathode. Over time, after the voltage has been applied to the cable for 5 minutes, 30 minutes, and 1 hour, charges appear within the insulation layer with increasing density and deeper penetration into the insulation, both for positive and negative charges.

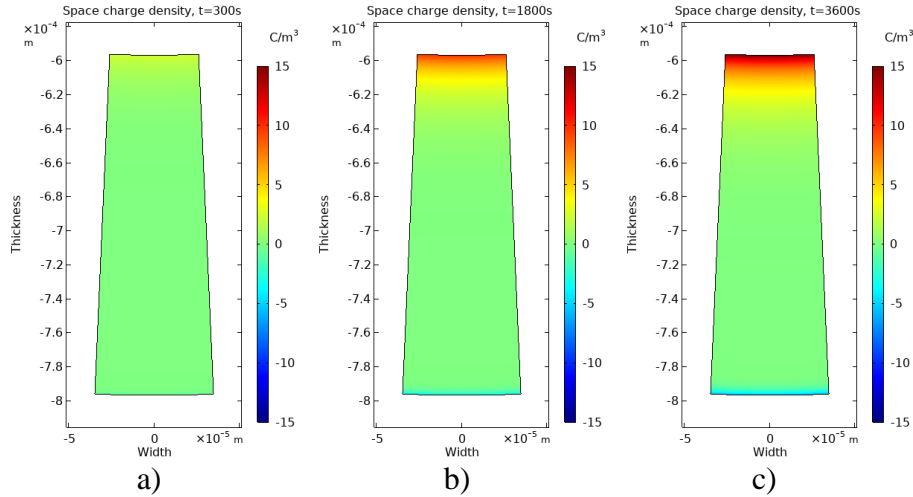


Fig. 3. Space charge distribution in the XLPE insulation layer with an ideal smooth surface when the cable is polarized by an electric field of 16kV/mm after a) 300, b) 1800 and c) 3600s

Each surface of the insulating layer contains defects:

In the second simulation, it is assumed that each dielectric surface has a $1\mu\text{m}$ defect in the center to examine the influence of defects on the space distribution of electric charge and the mutual influence of two symmetric defects on the dielectric surfaces. The simulation results in Figure 4a indicate that at the defect positions, the injection of positive charges from the anode and the injection of negative charges from the cathode into the dielectric occur more strongly than on smooth surfaces. Observing the insulating sample at the defect positions, we see a significant increase in charge density compared to the surrounding area and extending deep into the insulating material. In the region surrounding the defects, the amount of injected charge is smaller than in the case of an ideal smooth surface. It is even more pronounced for positive charges, arising from the anode, i.e. from the inner SC, than for negative charges, arising from the outer electrode, due to a higher electric field at the anode. The presence of a defect at the anode, coupled to a higher electric field in this region, over-increases the injection of charges. However, due to the thickness of the cable insulating layer, the respective positive and negative charges are injected from the anode and cathode into the dielectric at the positions of the symmetric defects on the two surfaces, without encountering each other within the dielectric. This results in the interaction between the opposite charges injected through the defects, such as charge recombination, not occurring. Therefore, in the next simulation, the influence of closely spaced defects only needs to be considered on one insulating surface to save computational resources.

The insulating layer near the anode surface contains a cluster of defects:

In this simulation, five defects with a diameter of $1\mu\text{m}$ are arranged closely together on the dielectric surface (Figure 4b). Similar to the previous simulation, at the positions of

the defects, the injected charge has a higher density and penetrates deeper into the dielectric material compared to the smooth surface. However, the observed shape of the positive charge cluster for each defect is not the same among the five closely spaced defects simulated. This can be attributed to the repulsive interaction between nearby positive charge clusters. When compared to the cases of a smooth surface (figure 3) and a surface with an isolated defect (figure 4a) for same polarized time, it is observed that the density of positive charge injected into the dielectric cluster is higher at positions with a smooth surface. Similarly, as observed in the previous simulation, around the defects, the density of positive charge appears to be lower than normal, as a large amount of charge is concentrated to pass through the defect.

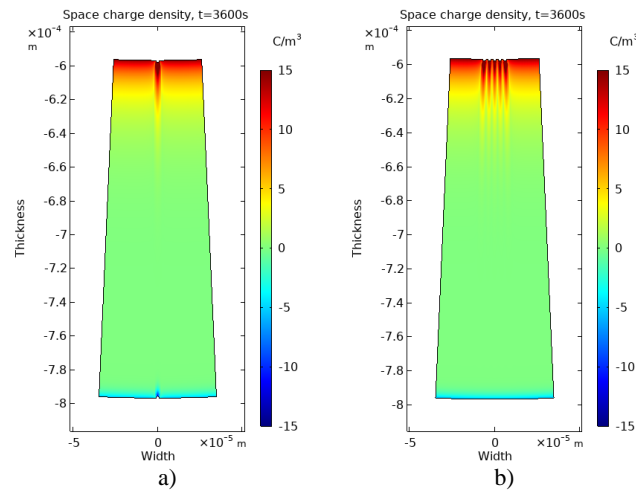


Fig. 4. Space charge distribution in XLPE insulation with a) both surfaces containing defects and b) a surface containing a defect cluster, when the cable is polarized by an electric field of 16kV/mm after 3600s

To compare the space charge distribution within the insulating layer of the HVDC cable at the center-sample defect in the three performed simulations, this study conducts a cross-section at the center of the dielectric layer along the radial line of the cable. Figure 5 depicts the characteristic curve of the space charge density as a function of the thickness of the insulating layer for the three surface conditions. In the case of non-ideal surface, it is evident that the space charge density on both sides of the surface significantly increases, nearly twice as much as the ideal smooth surface case. At the surface near the anode, the space charge density at the center defect is higher in the case of a single isolated defect compared to the clustered defects. As discussed earlier, this is due to the repulsive interaction between nearby positive charge clusters.

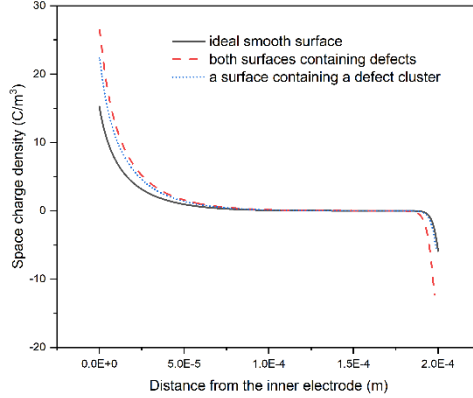


Fig. 5. Space charge density as a function of insulation layer thickness with different surface conditions when the cable is polarized by an electric field of 16kV/mm after 3600s

3.2 Influence of the Insulating Layer Surface Condition on Electric Field Distribution

The results of the three simulations presented in section 3.1 also have the ability to describe the electric field distribution within the HVDC cable insulating layer. In this section, the paper examines the influence of the surface condition on the electric field distribution within the insulating layer when the cable is polarized under an external electric field of 16 kV/mm. Firstly, the time-dependent electric field distribution since the voltage is applied to the cable with an ideal smooth insulating surface is considered in Figure 6. The Laplacien field, at $t=0$ s, presents a higher electric field at the anode ($x=0$) than at the cathode, with a mean applied electric field of 16 kV/mm. When charges are injected, they decrease the electric field. This is particularly the case at the anode, as the electric field is higher, so the injection is higher. The electric field maximum changes then from the anode side to $x=0.2$ mm after one hour. It also mean that the steady state is not reached after one hour of applied voltage. Therefore, the field values vary insignificantly at their maximum values

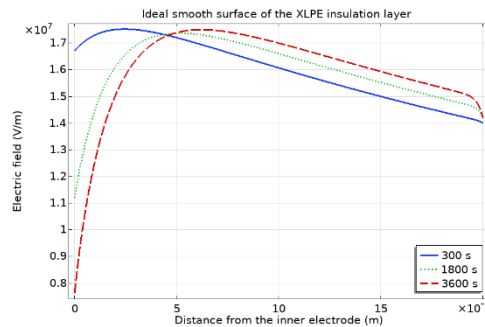


Fig. 6. Electric field distribution in an insulating layer with an ideally smooth surface after different time periods since the cable was placed under the external electric field

The electric field characteristic curves along the insulation thickness corresponding to three surface condition cases are shown in Figure 7, after one hour of applied voltage.

The fundamental differences are observed in the initial and final portions of the three characteristic curves, corresponding to the regions of electric charge injection into the insulation layer through the presence of defects. In the case of defects on the surface, the value of the electric field, due to this defect, increases drastically. It can be seen that the electric field is doubled at the anode and at the cathode. Meanwhile, the electric field remains the same as in the case of a smooth surface in the bulk of the material. highest electric field value is observed when defects are present on the surface adjacent to the cathode, reaching nearly 28 kV/mm, which is significantly higher than the operational electric field of the cable at 16 kV/mm. This can accelerate the aging process of the insulation material or lead to phenomena such as partial discharge when the external electric field applied to the cable is higher, even if the value is still far below the breakdown threshold of the dielectric.

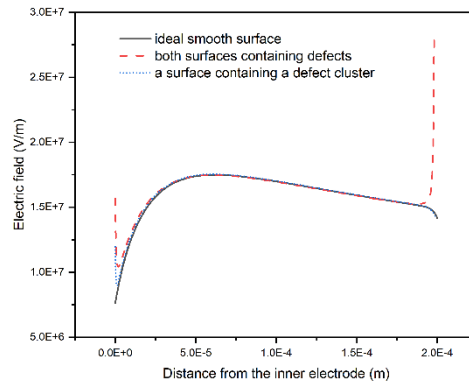


Fig. 7. Electric field distribution in the insulation layer with different surface conditions when the cable is exposed to an external electric field of 16kV/mm after 3600s

4 Conclusions

Influence study of the surface condition of the insulating layer on the space charge distribution of electric charge and the electric field distribution within the HVDC cable insulating layer was carried out on a sample of XLPE insulation material using three 2D simulations conducted with Comsol Multiphysics® software. The space charge density and electric field values significantly increase at the position of defects appearing on the surface compared to the case of an ideal smooth insulating surface, although the two surfaces containing defects do not have a mutual influence due to the large thickness of the cable's insulating layer. When defects appear simultaneously, the charge density increases significantly in the region near the insulating surface. However, the charge density and electric field intensity at the center defect within the cluster of defects tend to decrease compared to the case of an isolated defect. Therefore, the insulating layer surface containing defects can adversely affect the insulation layer of the cable, such as accelerating the aging process or causing partial discharge within the cable. Further studies can be conducted to better understand the detrimental effects of surface defects on the electrical characteristics of HVDC cables, including the variation of cable operating temperature and increased electric field intensity to higher levels, which may pose a risk of localized partial discharge or insulation breakdown.

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